Navier-Stokes Analysis of Airfoils with Gurney Flap

Manish K. Singh, K. Dhanalakshmi and S. K. Chakrabartty
Computational and Theoretical Fluid Dynamics Division
National Aerospace Laboratories
P. B. 1779, Bangalore 560 017, India

Abstract

Two dimensional steady state Navier-Stokes computations were performed to determine the effect of Gurney flap on NACA 4412 and NACA 0011 airfoils. Gurney flap sizes selected for the study range from 0.5% to 4% of the airfoil chord. A compressible Navier-Stokes solver with Baldwin-Lomax turbulence model, JUMBO2D, is used to predict the flow field around the airfoils. Computed results have been compared with available experimental and computational data. There is good correlation observed between computed and experimental data. Addition of Gurney flap increases the lift coefficient significantly with very little drag penalty if proper Gurney flap height is selected. Nose down pitching moment also increases with Gurney flap height. Flow field structure near the trailing edge shows very good resemblance with Liebeck's hypothesis that provides the possible explanation for the increased aerodynamic performance.

1. Introduction

High lift systems play a major role in performance and economic success of commercial, transport and military aircraft. An efficient high lift system offers many advantages like lower take off and landing speed, greater payload capacity for given wing, longer range for given gross weight and higher manoeuvrability. High lift systems are desired to maintain low drag at take off so as to attain cruise speed faster and high drag at approach. High lift systems are often quite complex consisting of many elements and multi bar linkages. Therefore there is need to have simpler high lift systems which are cheaper in terms of manufacturing and maintenance cost. One such candidate is Gurney flap.

Gurney flap is a small flat plate, in the order of 1-2% of airfoil chord in height, fitted to pressure side of airfoil at the trailing edge and perpendicular to the chord line. Don Gurney first used this trailing edge device in racing car to increase the down force during high velocity cornering [1]. He noticed drag reduction, which he measured by a comparison of corner and straightaway speeds with and without Gurney. He also found that increasing the Gurney flap height beyond 2% of chord led to increase in the down force but at the cost of significant drag penalty.

Liebeck [1] conducted wind tunnel tests on the Newman airfoil with 1.25% chord Gurney flap. He found that lift increased for given angle of attack and drag reduced for given lift. Tufted probe at the trailing edge indicated significant turning of flow over the backside of Gurney flap. He hypothesized that Gurney flap causes flow to turn towards flap near trailing edge by introducing two counter-rotating vortices aft of the Gurney flap [Fig. 1].

Myose et. al. [2] conducted low speed wind tunnel tests on NACA 0011 airfoil with Gurney flap heights ranging from 1% to 4% of the chord. They noticed that Gurney flap increases the upper surface suction and lower surface pressure thereby resulting in lift increment. They also reported increase in nose-down pitching moment due to Gurney flap. The wake velocity profiles plotted by them indicate downward turning of the flow behind the airfoil due to presence of Gurney flap. They concluded that Gurney flap works by increasing the effective camber of airfoil.

Jang et. al. [3] used an incompressible Navier-Stokes code to compute flow field about NACA 4412 airfoil with Gurney flap heights ranging from 0.5% to 3% of chord. Computations predicted increase in lift coefficient and nose down pitching moment. Computations also show that at moderate angle of attack Gurney flap causes separation points on suction surface to shift aft as compared to clean airfoil. They noticed increment in loading along entire length of the airfoil when Gurney flap is used.

Storm and Jang [4], who conducted experimental study on same airfoil with Gurney flap, reported similar trends. However, they observed that though there is good correlation between experiment and computational lift coefficient obtained by Jang et. al. [3] for clean airfoil, computations seem to under predict the lift increment caused by Gurney flap.

The primary objective of the present work is to study the flow past NACA 4412 and NACA 0011 airfoils with Gurney flaps of different heights using the compressible Reynolds averaged Navier-Stokes analysis code JUMBO2D and to compare these results against available experimental and computational results.

2. JUMBO2D Solver Code

The JUMBO2D computer code solves the two-dimensional Reynolds Averaged Navier Stokes (RANS) equations using a vertex based finite volume space discretization and five-stage Runge-Kutta time integration. Local time stepping, enthalpy damping and implicit residual smoothing are used for convergence acceleration. Baldwin-Lomax [5] turbulent model is used for the computation of turbulent flow. Details of the governing equations, boundary conditions, finite volume formulation, time integration and the turbulence model used are available in literature [6,7,8,9].

The code is independent of the grid topology used, and the only necessary input is the grid data. The computational domain can be subdivided into smaller sub-domains/blocks and the computation can be carried out block wise to reduce the current memory requirement and to facilitate parallel computation. Overlapping one layer of grid cells connects the blocks, and using, in the input data, an apriori specification of the proper block connections, transfers the boundary data. The type of the boundary conditions to be specified at each segment of a face of a particular block can be specified through input data. These make the code very flexible, and allow the same code to solve a variety of flow problems. A novel space discretization scheme is used here for the viscous terms, which facilitates computation of full Navier-Stokes equations with about the same numerical effort as for the thin layer type of approximation [6].

3. Geometrical Modeling and Grid Generation

NACA 4412 and NACA 0011 airfoils are considered for this study. Gurney flap sizes of 0.5%, 1%, 1.5%, 2% chord length were chosen for NACA 4412 airfoil and 1%, 2% and 4% of chord length for NACA 0011 airfoil. These particular Gurney flap sizes are considered in order to make comparison with available experimental and computational results. Gurney flaps with zero thickness (i.e. coinciding with a grid line) were also tried but the solutions did not vary significantly from the present results, where the thickness of the flap is equal to the width of one grid cell.

Commercially available grid generation software Gridgen [10] has been used to generate structured grids. Hyperbolic tangent distribution function is used to determine the point distribution on the boundaries. Transfinite interpolation is employed to determine interior point distribution and Elliptic PDE method has been used to smooth and improve grid quality. A single block C-type structured grid has been generated for computing the flow field for clean airfoils. A three-block structured grid (Fig. 2 and 3), with one block below the wake centre line, another block around the airfoil and the third one above the wake centre line, is employed to compute the flow field for airfoils with Gurney flaps. The dimensions of grids are listed in table 1. The upstream, downstream, top and bottom boundaries are located at 16 chord lengths away. The first grid point above the airfoil surface is such that the law of the wall coordinate y+ is of the order of 5. Various grid dimensions and far-field distances were tried and the present grids were found to be optimum in capturing the complex flow physics of the Gurney flap. For the application of turbulence model, in the vicinity of Gurney flap, normal distance is taken as the minimum of the two distances measured from the airfoil surface and the Gurney flap.

Table 1: Grid Dimension

NACA 0011	Block Number		
	I	II	III
Clean Airfoil	347x62		
1% chord Gurney	45x62	258x62	45x62
2% chord Gurney	45x91	258x91	45x91
4% chord Gurney	70x91	358x91	70x91
NACA 4412	**Block Number**		
	I	II	III
Clean Airfoil	497x62		
0.5% chord Gurney	70x73	358x73	70x73
1% chord Gurney	70x91	358x91	70x91
1.5% chord Gurney	70x91	358x91	70x91
2% chord Gurney	70x91	358x91	70x91

4. Results and Discussion

All the computations in this study for NACA 4412 airfoil are performed for free-stream Mach number of 0.20 and chord Reynolds number of 2.0 million and those for NACA 0011 airfoil are carried out for Mach number 0.14 and chord Reynolds number of 2.2 million. These flow parameters for computations were chosen in order to make comparison with available experimental results. The JUMBO2D solver code used in the present analysis has been extensively validated and applied to a variety of flow problems [6,9,11,12].

Fig. 4 shows comparison of pressure coefficient between experimental [4], incompressible computation [3] and present computation of NACA 4412 airfoil with 1% chord Gurney flap. Present Cp distribution lies between those obtained by experiment and incompressible flow results on the upper surface of the airfoil whereas on the lower surface there is no significant difference between those obtained by compressible and incompressible computation.

Comparison of lift coefficient C_L, drag coefficient C_D, quarter chord moment coefficient C_M and coefficient of pressure distribution C_P are shown in figures 5 and 6 for NACA 4412 and NACA 0011 airfoils respectively. It is evident from lift coefficient comparison that there is significant nonlinear increment in lift with Gurney flap height. For example, lift increment due to Gurney flap of 1% chord height with respect to the clean airfoil is higher than that obtained by changing Gurney flap height from 1% chord to 2% chord in both airfoils. Computational results predicted stall angle higher by 2-3 degree (as compared to the experimental results). Under pre-stall conditions it is observed that there is good agreement between computational and experimental data for NACA 0011 airfoil with and without Gurney flap except 4% chord Gurney case where computations seem to under predict the lift coefficient. It is also noted that computations are over predicting the lift compared to experiment for NACA 4412 airfoil with and without Gurney and the difference between computation and experiment is increasing with angle of attack. These differences are probably due to the fact that flow is increasingly becoming unsteady at higher angle of attack and particularly beyond stall while computations assume flow to be steady. Comparisons of drag coefficient suggest that, up to stall, there is no significant drag increment with addition of Gurney flap, if Gurney flap height is restricted to about 2% of chord. This result is in good agreement with Liebeck [1] who concluded that increasing the Gurney flap height beyond approximately 2% increases the drag substantially. Experimental study of NACA 0011 airfoil with Gurney flap by Myose et al. [2] shows that boundary layer thickness is about 1.5% of chord near the trailing edge at zero angle of attack. So, there would not be significant drag increment if Gurney flap height were kept within this limit, as most of the device remains buried within the boundary layer. Similar to the lift coefficient, quarter chord pitching moment increases with Gurney flap height but increment becomes less with increasing Gurney flap heights. It is evident from airfoil pressure coefficient comparison that the presence of Gurney flap increases the pressure difference between the upper and lower surfaces of the airfoil especially near leading and trailing edge. This leads to increase in lift coefficient. An increase in Gurney flap height also produces a similar effect. It can be noted that there is adverse pressure gradient caused by Gurney flap near the trailing edge on pressure side of airfoil and upstream of Gurney flap. Mach contours and streamlines in the vicinity of the trailing edge are shown in Fig. 7 for NACA 4412 airfoil with 2% chord Gurney flap. Three vortices, one upstream of Gurney flap and two counter rotating vortices downstream of the flap, can be seen. It is observed from the flow field comparison that Gurney flap causes flow to turn downward beyond the flap. This is in agreement with Liebeck's [1] wind tunnel test, where tufted probe indicated significant turning of the flow downstream of the flap. The adverse pressure gradient observed upstream of the flap on the lower surface may be attributed to the formation of recirculating / cove vortex.

5. Conclusion

Compressible flow past NACA 4412 and NACA 0011 airfoils with Gurney flap has been studied in detail using a RANS code (JUMBO2D) with algebraic turbulence model. Computational results are found to agree reasonably well with available experimental data. Use of Gurney flap increases lift coefficient and nose down pitching moment compared to those obtained for clean airfoil, however these increments are nonlinear with respect to flap height. There is no significant increase in drag if Gurney flap height is kept within boundary layer, however beyond this limit drag increment is significant. The presence of Gurney flap increases the upper surface suction and the lower surface pressure causing increment in loading along entire length of airfoil, noticeably near the trailing edge. Flow field comparison shows that addition of Gurney flap causes downward turning of the flow behind the Gurney flap.

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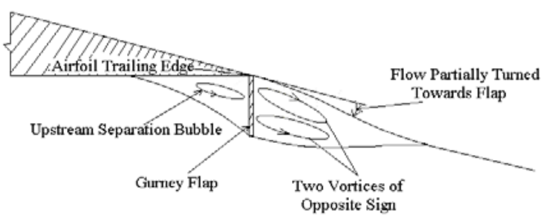


Fig. 1: Hypothesized trailing-edge flow field for an airfoil with Gurney Flap [1]

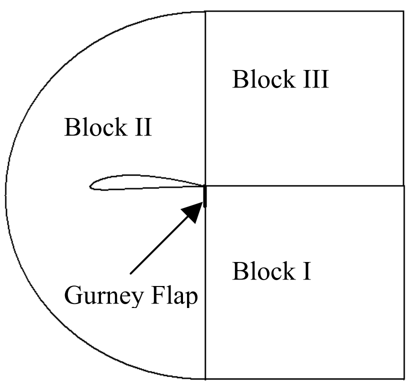


Fig. 2: Block arrangement for computation of flow past airfoil with Gurney flap

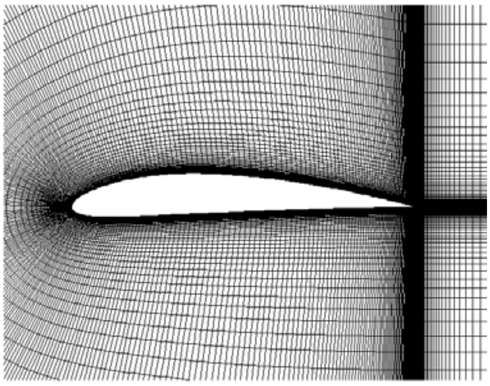


Fig. 3: Close up of grid in the vicinity of airfoil

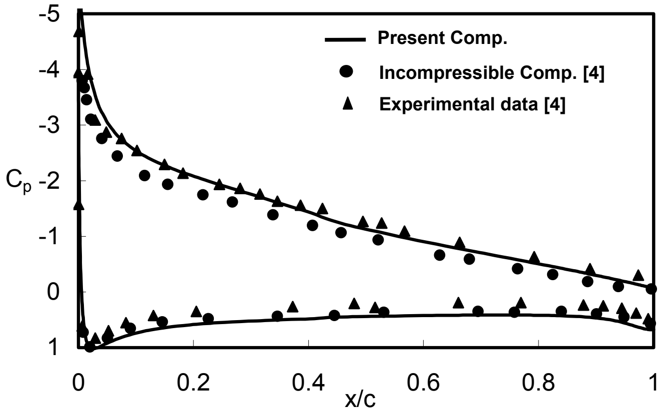
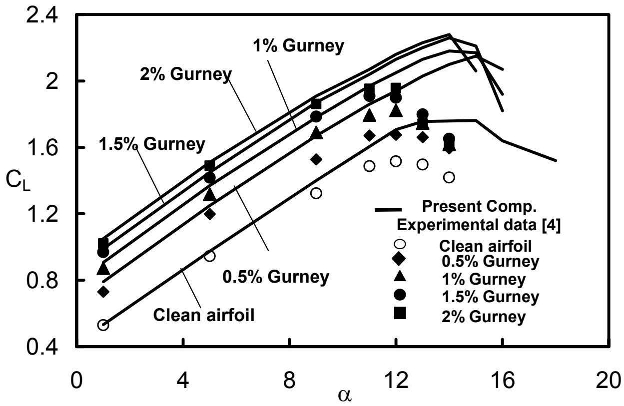
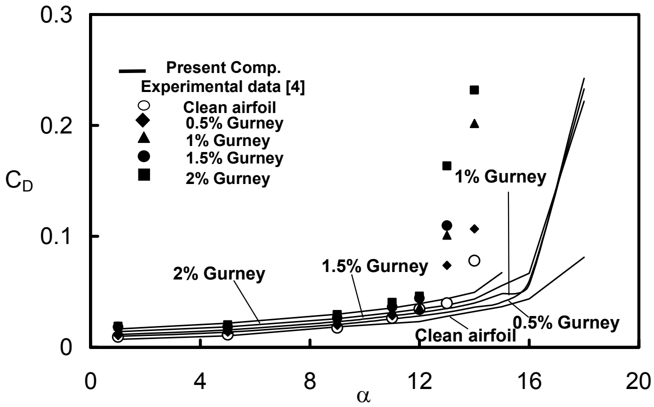


Fig. 4: Comparison of pressure coefficient of NACA 4412 airfoil with 1% chord Gurney at α=9°



(a)



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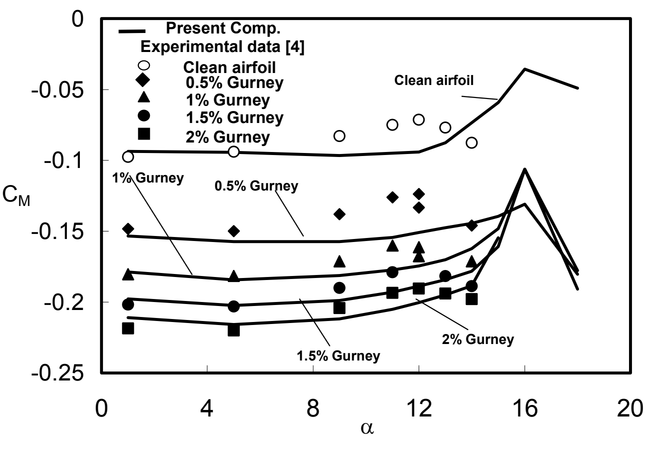

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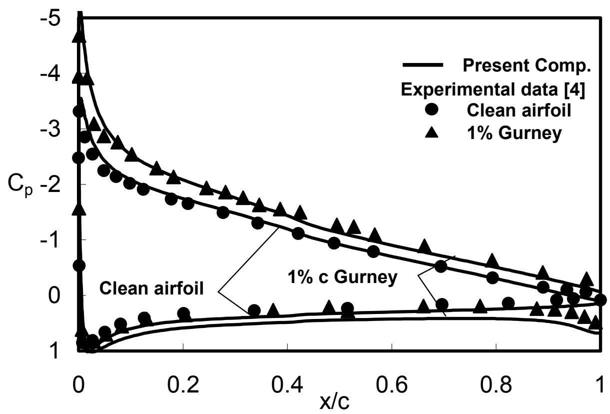

(d)

Fig. 5: NACA 4412 airfoil (a) Comparison of airfoil Lift coefficient between computations and experiment for various Gurney flap sizes (b) Comparison of airfoil Drag coefficient between computations and experiment for various Gurney flap sizes (c) Comparison of Quarter chord pitching moment for various Gurney flap sizes (d) Pressure coefficient comparison between computations and experiments at α=9°

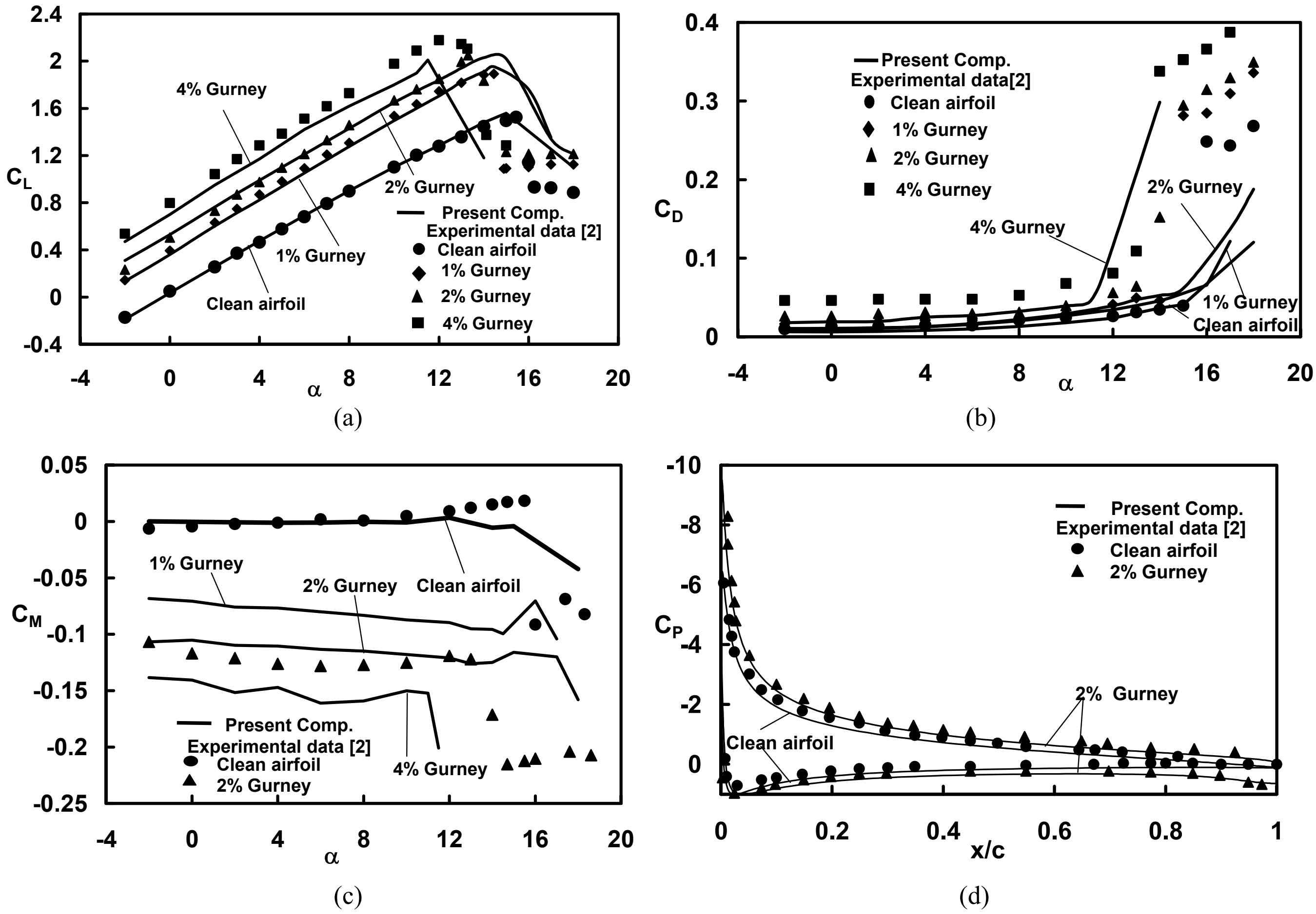

Fig. 6: NACA 0011 airfoil (a) Comparison of airfoil Lift coefficient between computations and experiment for various Gurney flap sizes (b) Comparison of airfoil Drag coefficient between computations and experiment for various Gurney flap sizes (c) Comparison of Quarter chord pitching moment for various Gurney flap sizes (d) Pressure Coefficient comparison between computations and experiments at α=10°

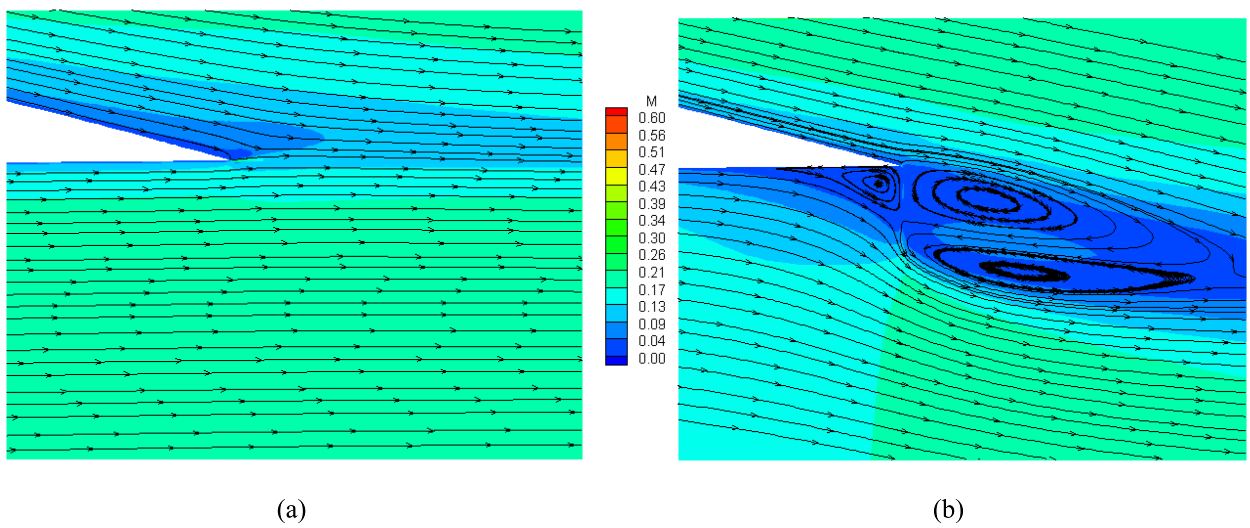

Fig. 7: (a) Mach contour & stream lines around trailing edge of clean NACA 4412 airfoil at α=5° (b) Mach contour & stream lines around trailing edge of NACA 4412 airfoil with 2% chord Gurney flap at α=5°